Non-perturbative QCD Effects and the Top Mass at the Tevatron

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Based on work with Peter Skands
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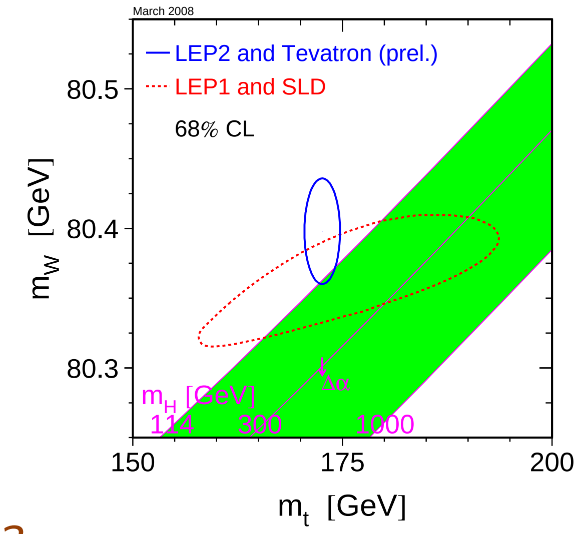
Introduction

The top mass is the only free parameter of the SM special to top physics

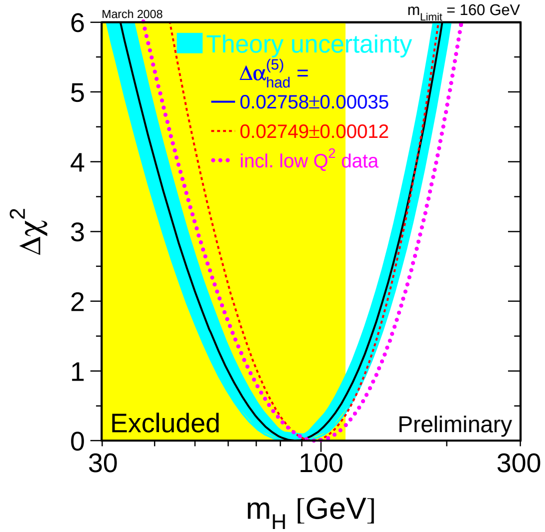
Direct measurements and indirect determinations
from EW precision observables

- used to check consistency with SM
- used to predict Higgs mass



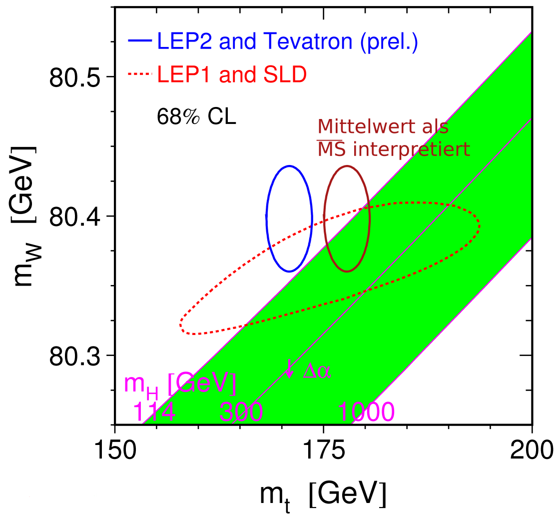
But do direct/indirect results talk about the same mass?

- Required for consistency checks and M_H prediction
- EW precision fits use $\overline{\mathrm{MS}}$-mass
- Direct measurement calibrate to MC (Pole mass?)



Introduction (II)

- If difference between pole and $\overline{\mathrm{MS}}$-mass was ignored SM consistency would look quite different $\longrightarrow$ (We're not *that* stupid)



- Assumption that MC have LO mass is accounted for
- But MCs implement more than LO: Parton shower, Modelling of non-pert. effects, ...

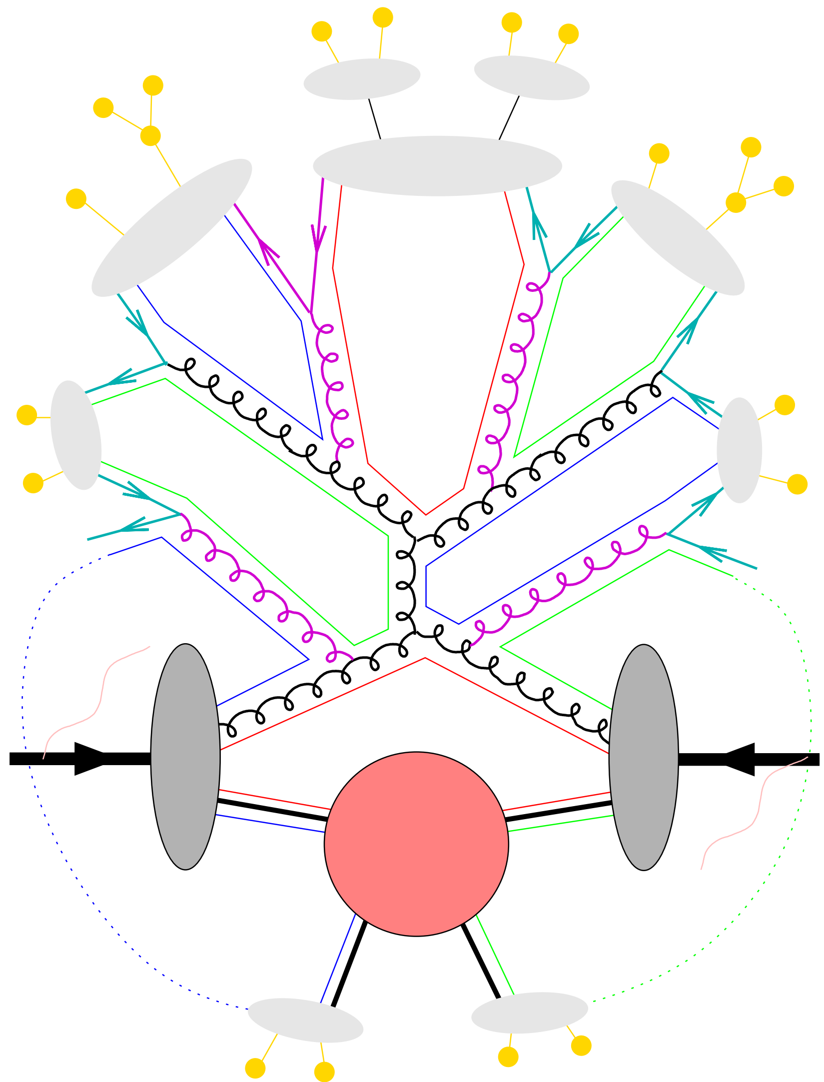
Confinement / Soft QCD / Non-perturbative QCD

- ... introduces ambiguities to the mass definition
- ... governs Underlying Event
- ... governs Colour Reconnection

these may alter the meaning of the mass determined

Modelling

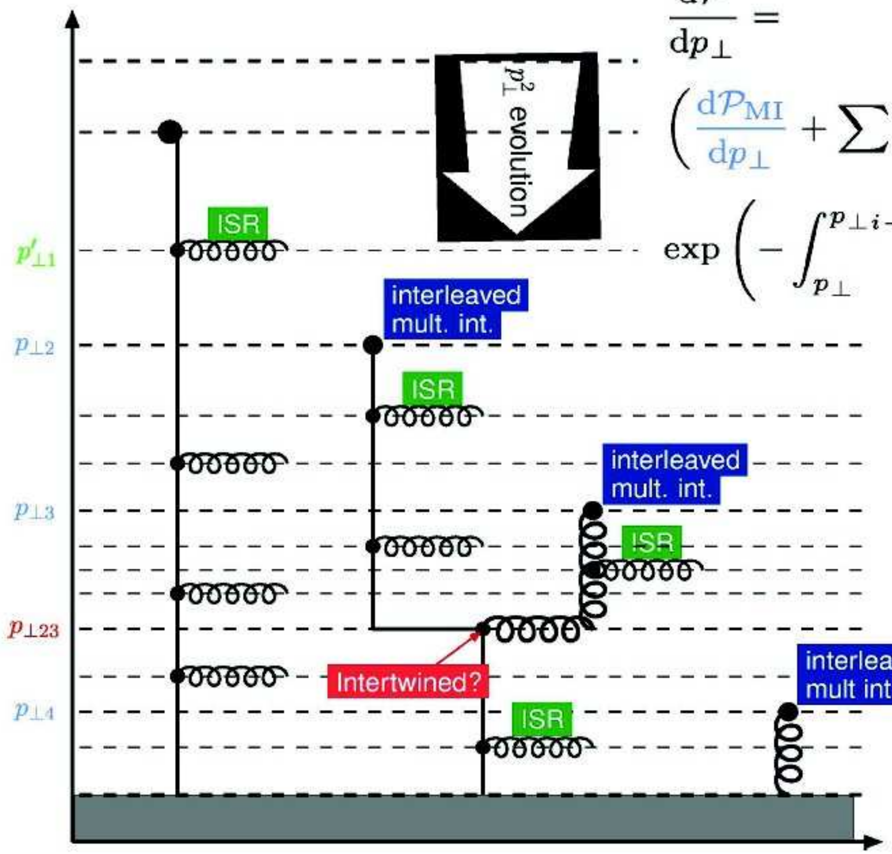
- PDFs
- ISR
- Hard Process
  $2 \rightarrow 2(3)$, $2 \rightarrow$ many; LO, NLO
  Scales
- Parton Shower
  various PS; matched or unmatched
- Colour reconnection (CR)
- Hadronisation
- Decays
- Underlying Event (UE)



Some steps not computed from first principles $\Rightarrow$ Modelling required

Pythias Underlying Event Models

- Old: UE generated after the ISR is done, i.e. uncorrelated.
- New: Parton showers interleaved with UE. (Requires p_T ordered shower).



$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}p_\perp} = \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p_\perp} \right) \times \exp\left(- \int_{p_\perp}^{p_{\perp i-1}} \left(\frac{\mathrm{d}\mathcal{P}_{\mathrm{MI}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{ISR}}}{\mathrm{d}p'_\perp} + \sum \frac{\mathrm{d}\mathcal{P}_{\mathrm{JI}}}{\mathrm{d}p'_\perp} \right) \mathrm{d}p'_\perp \right)$$

⇨ successive "finegraining" of all perturbative activity

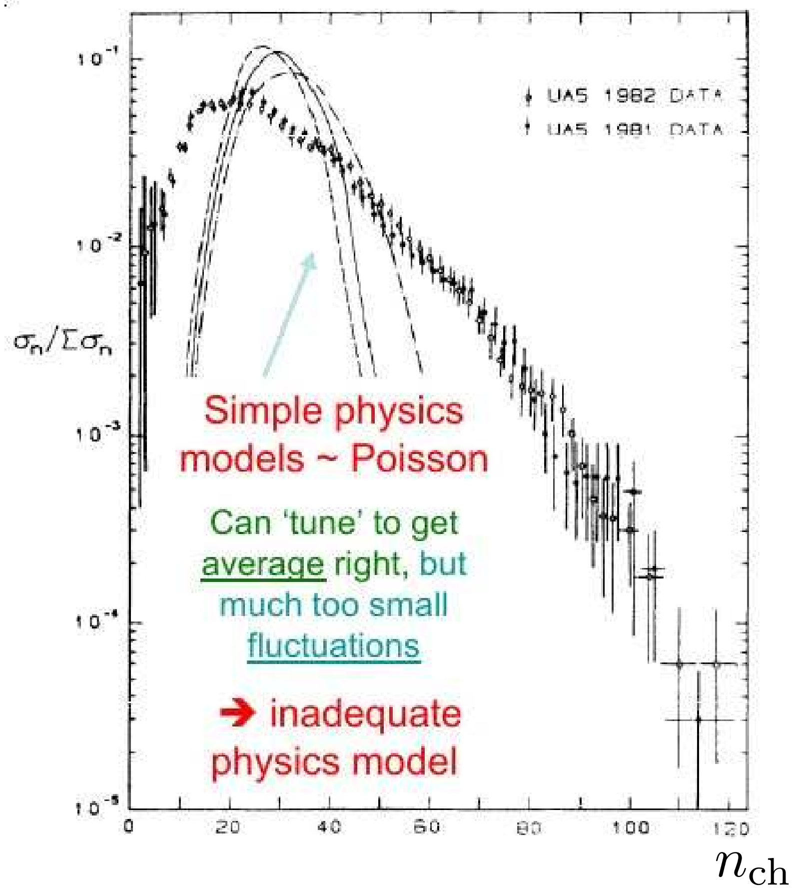
\+ correlated multiparton pdfs (with flavour/momentum cons)

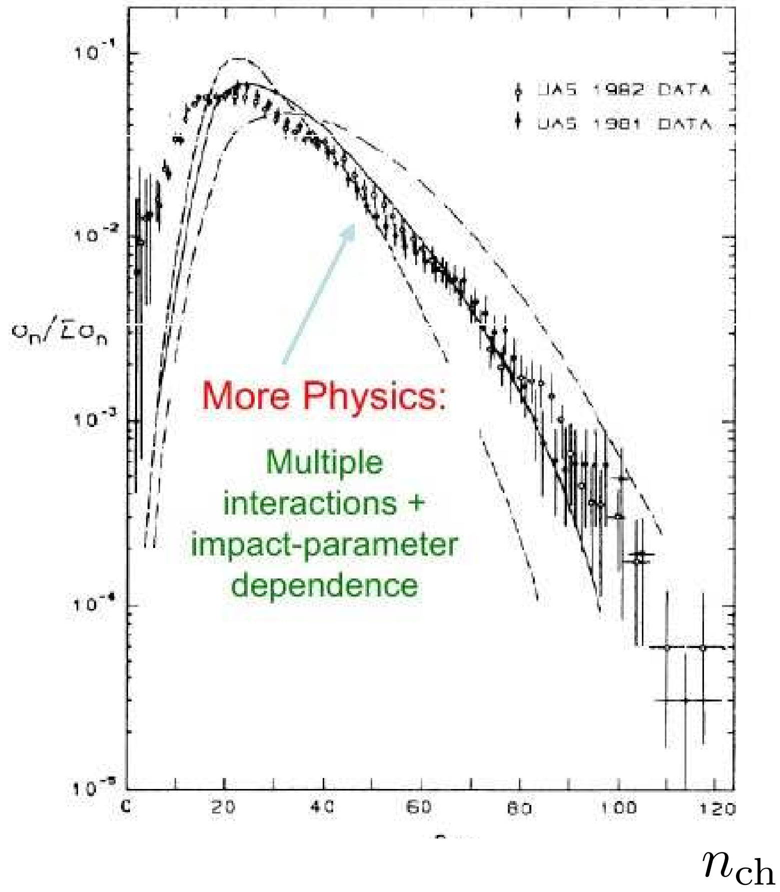
\+ Impact parameter dependence

\+ String fragmentation developed for baryonic colour topologies ⇨ improved description of beam remn.

Example of Sensitive Observable

Classic example UA5 @ 540 GeV: Charged multiplicity in min. bias events





Tuning *and* physics implementation needed to get good description

Current Tunes

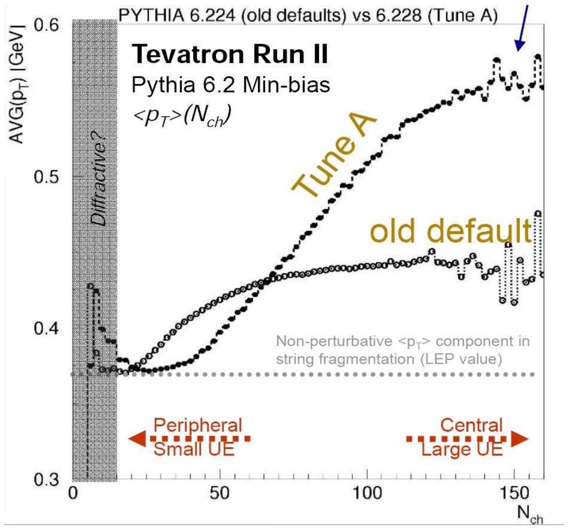
Tuning to min. bias data gave significant improvements

Several pythia tunes to min. bias data available

Tune A, Tune DW, Tune BW, ... (Rick Field)

These implicitly allow CR within UE to a high level:

PARP(85)	$0.33 \rightarrow 1.0$	Prob. for MPI w/ colour connection
PARP(86)	$0.66 \rightarrow 1.0$	to neighbours/ closed loop



Colour Reconnection

Is the colour-flow of the hard interaction preserved?

Proton remnants provide lots of (soft) gluons to interact with.

Most models were only available for $e^+e^- \rightarrow WW$

New Models by M. Sandhoff and P. Skands in Pythia 6.326+
Alternative models by Uppsala group / Webber not yet explored in this context.

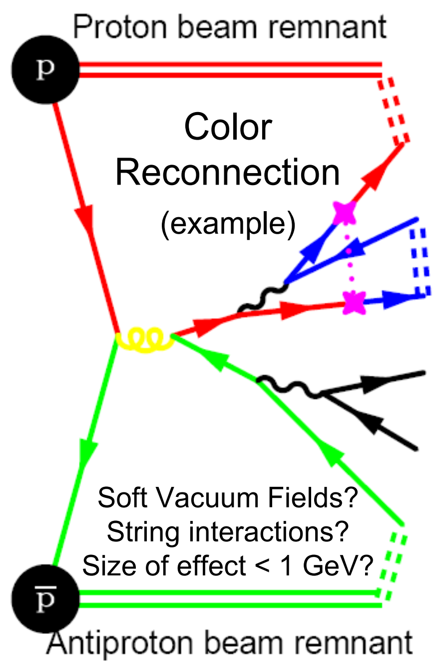
New CR Models: Colour Annealing

Allow CR also within the hard interaction.

- At hadronisation strings pieces may reconnect

$$P_{\text{reconnect}} = 1 - (1 - \chi)^n$$

  χ — strength parameter
  n — number of interactions
  (counts number of possible interactions)



- New connection chosen to minimise string length, i.e. minimise potential energy in strings
- Model variations: $S0$, $S1$, $S2$ differ in suppression of gluon only string loops

These models of colour reconnection are applicable to any final state.

Tuning the Models

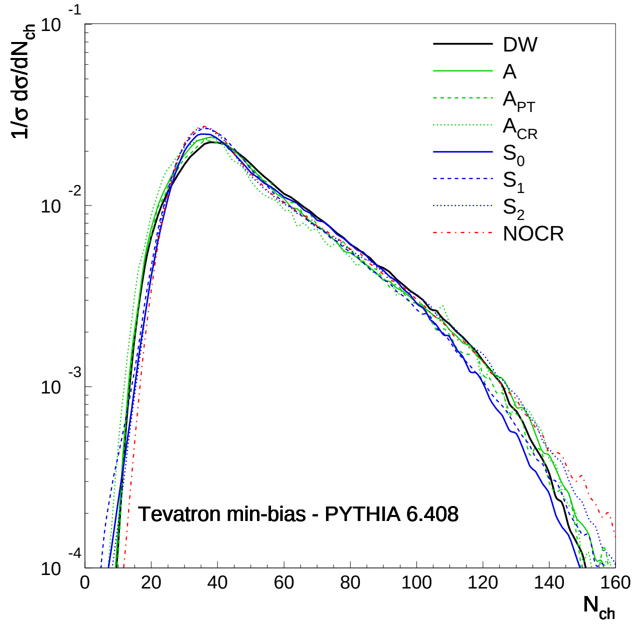
CR used in UE description $\Rightarrow$ retune both.

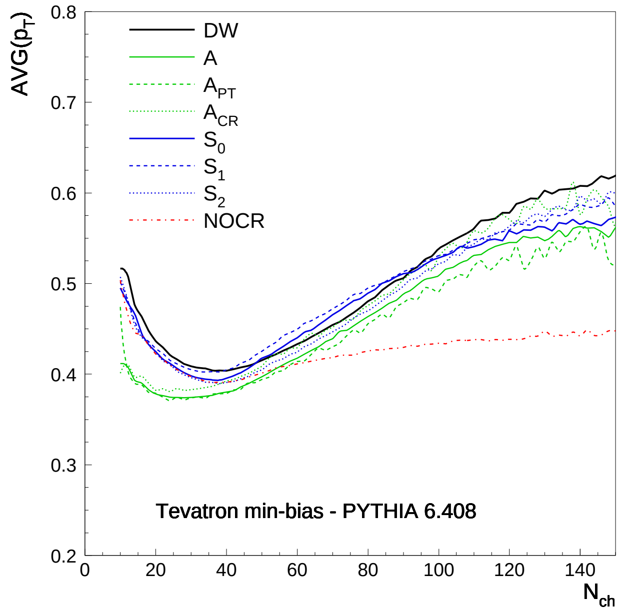
Tune A is known to describe data reasonably well.

Thus models tuned to it.

- New CR models were tuned to describe N_{ch} and $\langle p_T \rangle(N_{ch})$.
- Right: comparison of models.
  (Red is no CR, tuned)
- NoCR can't be made to agree:
  CR seems necessary to describe UE features.

New Models w/ tunes available in Pythia 6.408+.

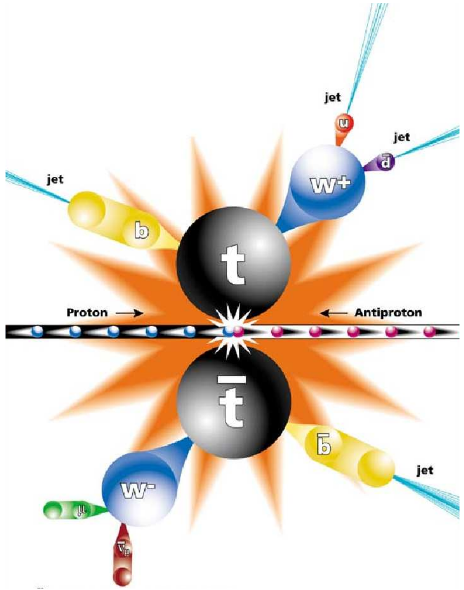




Top Mass Measurement

Features of Real Mass Measurements

Current real life mass measurements contain 3 important ingredients.



- Mass estimator
  - Reconstructed physics objects
  - Jet assignment (choose or weight)
- Overall JES correction factor
- Calibration of method
  - Uses Simulation $\Rightarrow$ may be affected by changes in CR models.

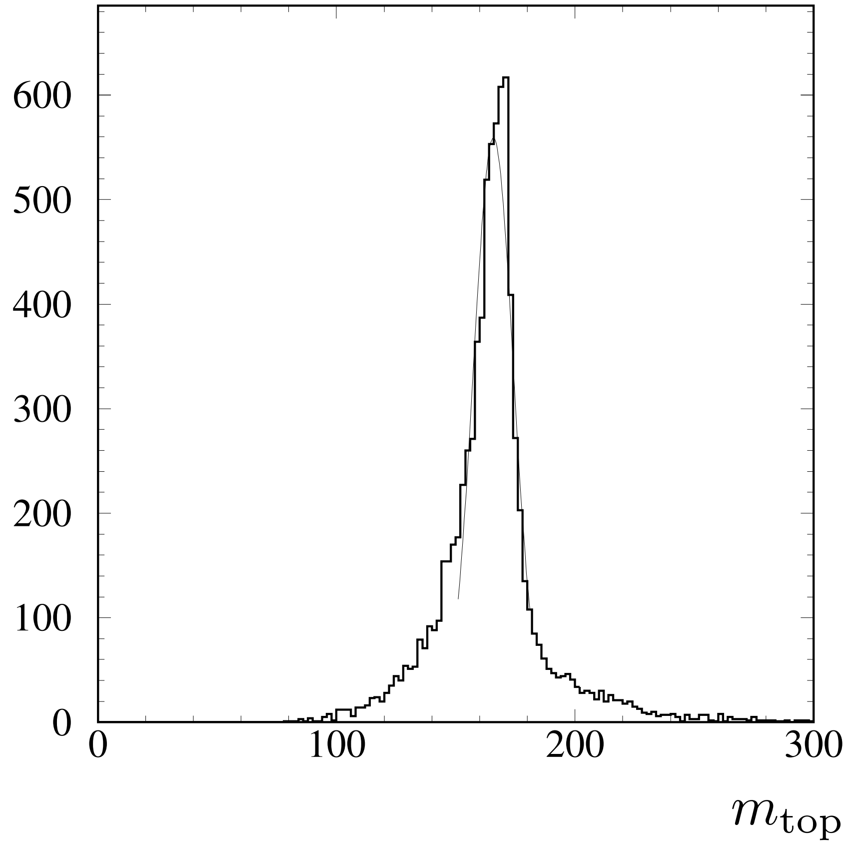
To concentrate on physics effects (and avoid dealing with detector simulation) a simplified toy mass measurement is implemented.

Toy Mass Estimator

- For each available model 100k inclusive events were generated
- Jets are reconstructed using Cone ($\Delta R = 0.5$, $p_T > 15\,\mathrm{GeV}$)
- Exactly 4 reconstructed Jets
- Technical simplifications:
  - Generator semileptonic events.
  - Unique assignment to MC truth by ΔR possible.
- Reconstruct mass on correct assignment only: $m^2 = (p_{b\,\mathrm{jet}} + p_{q\,\mathrm{jet}} + p_{q'\mathrm{jet}})^2$
  (using hadronic side)

Mass Distribution

- Reconstruct mass on each event.
- Fit distribution with Gaussian: $m_{\text{top}}^{\text{fit}}$.
  - Fitrange: ± 15 GeV (iterated to avoid bias).
  - Varied fit ranges in syst. studies.
  - Suffers from out of cone problems.
- Rescale using M_W
  - Analog to JES fitting
  - Fit W-mass from light jets
  - Scale with $s_{\text{JES}} = 80.4\,\text{GeV}/m_W$: $\quad m_{\text{top}}^{\text{scaled}} = s_{\text{JES}}\, m_{\text{top}}^{\text{fit}}$



This provides two mass estimators: $m_{\text{top}}^{\text{fit}}$, $\quad m_{\text{top}}^{\text{scaled}}$

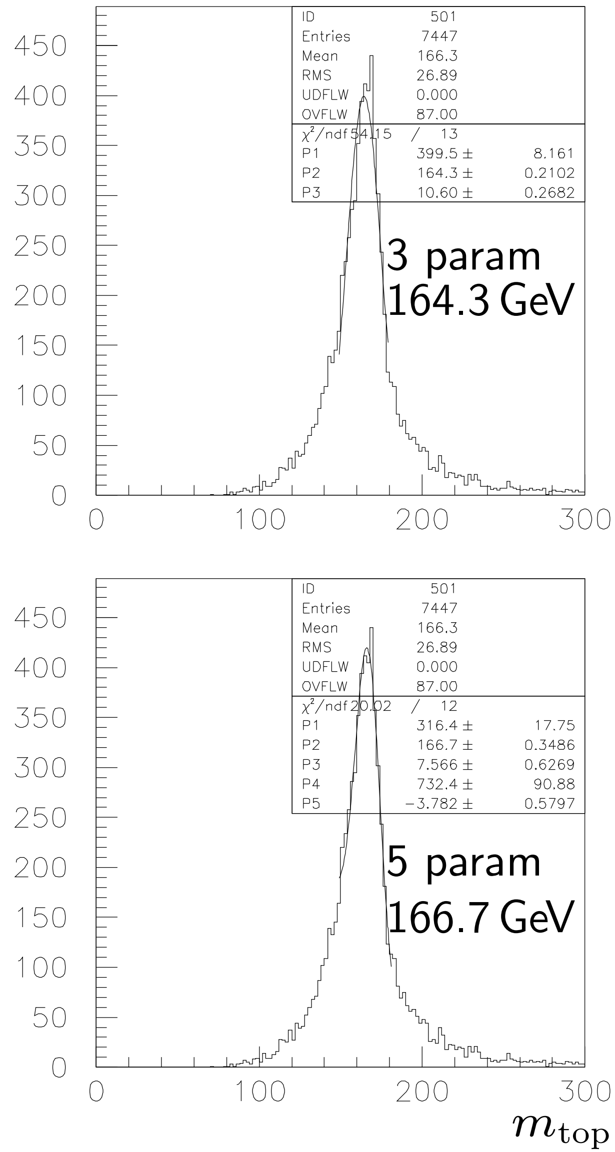
Alternative estimators

- Results depends on fit ranges.
- Thus each mass analysis needs to investigate its own sensitivity.
- Sensitive estimators might restrict models.

Alternative estimators include:

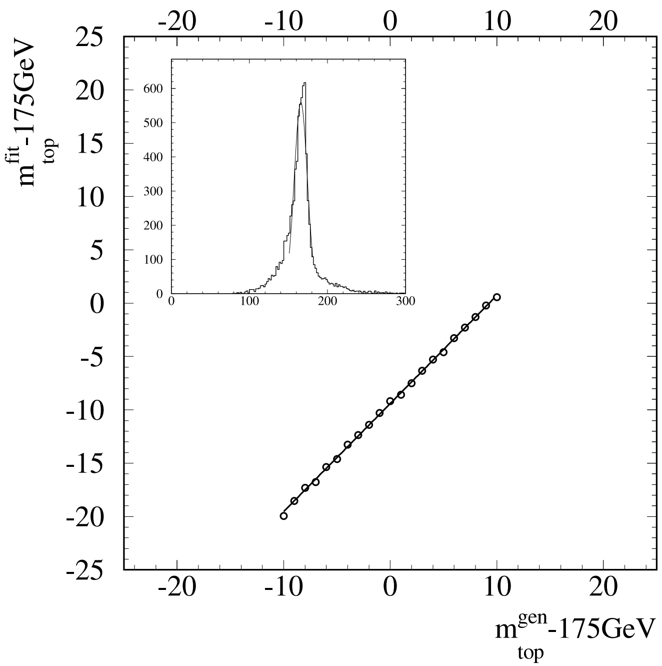
- Varied fit range sizes.
- Mean reconstructed top mass.
- More flexible function:
  Use gaussian + straight line
  (5 parameter fit)

All with and without m_W scaling.

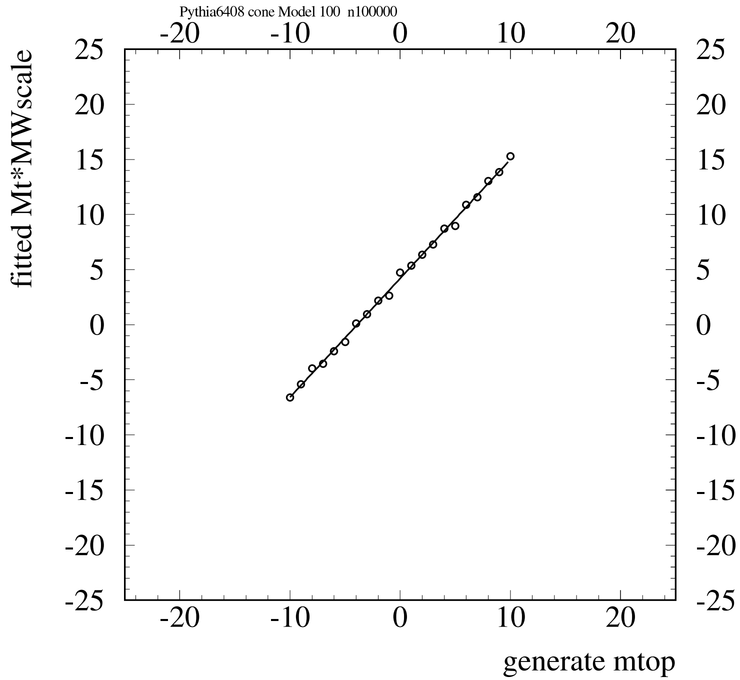


One toy analysis analysed in detail: ± 15 GeV fit range ($\sim$ exp. resolution)

Calibration Curves



rescale
$\longrightarrow$



- Calibration curves show reasonably linear behaviour
- Scaling with m_W does the right thing (offset significantly reduced)
- Fit straight line to obtain offset at 175 GeV

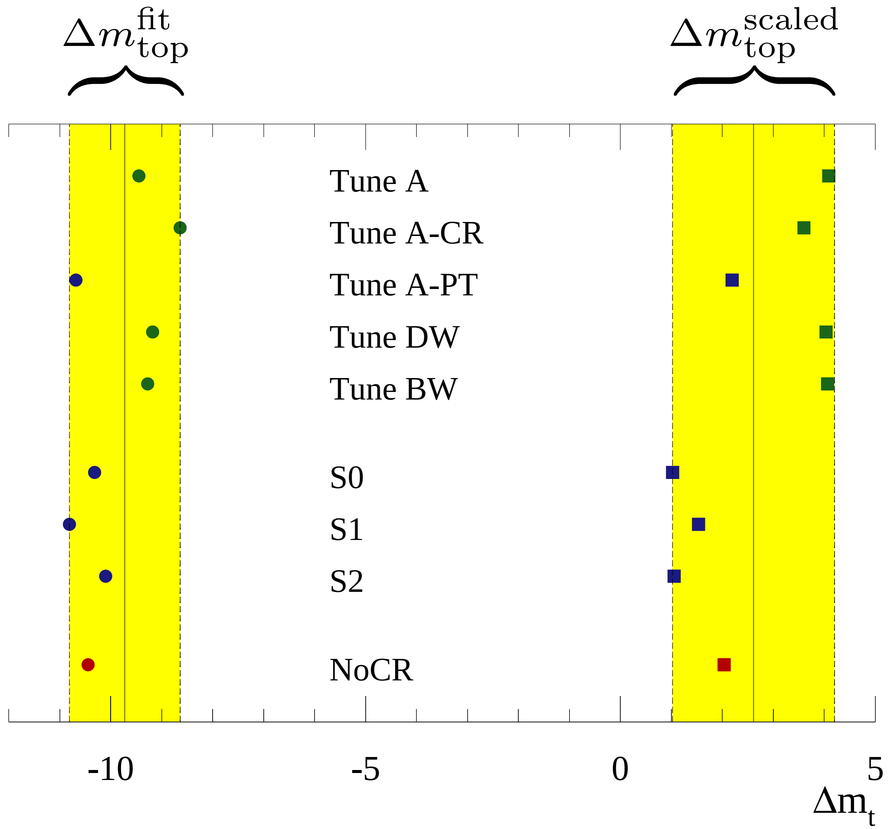
Procedure has been repeated for a various (tuned) models to compare offsets

Calibration uncertainty

- Offsets and slopes from normally used to correct measurement methods

- Model dependence is m_t uncertainty

- Spread of ± 1.5 GeV observed

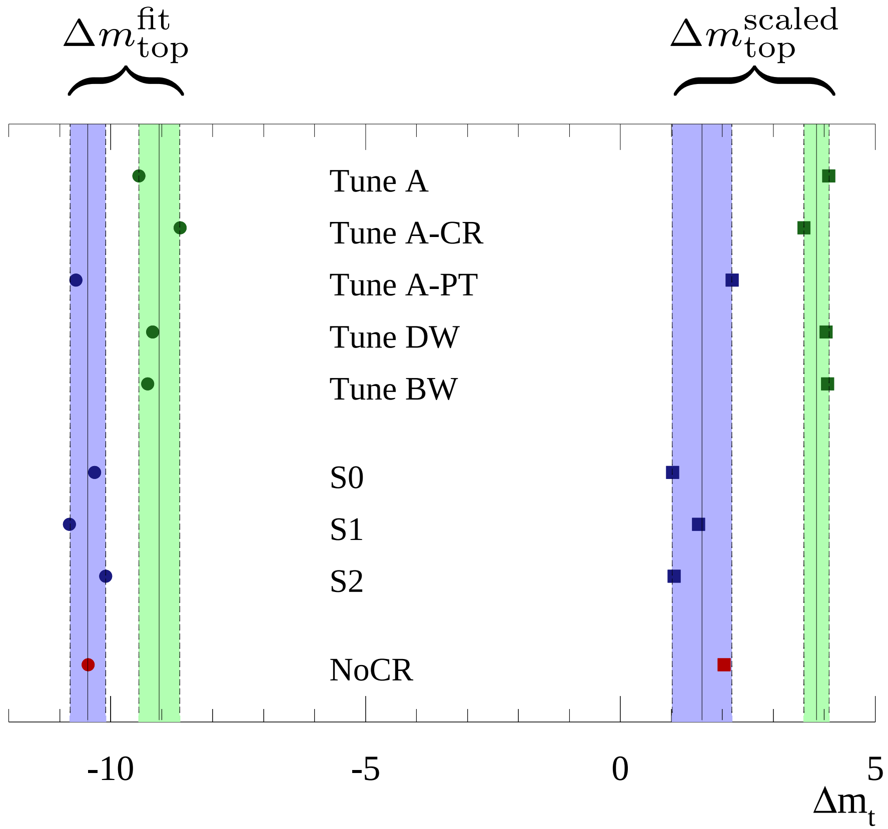


• – fitted m_t
sq – rescaled m_t

Cone Jet Algorithm
Fitrange ± 15 GeV

Calibration uncertainty

- Offsets and slopes from normally used to correct measurement methods



- Model dependence is m_{t} uncertainty
- Spread of ± 1.5 GeV observed
- 2 model classes with similar offsets
  - Virtuality ordered (old) Parton Sh.
  - P_T ordered (new) Parton Shower

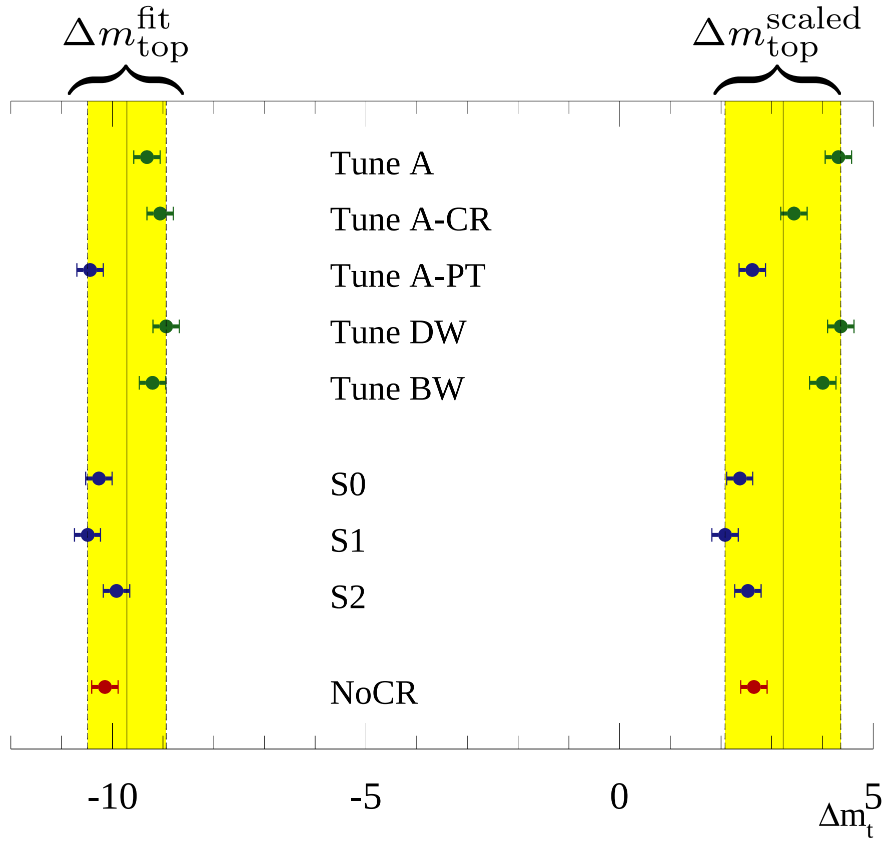
  Significant diff. of perturbative origin
- Within each group ~ 0.5 GeV of non-perturbative nature remain.

• – fitted m_t
sq – rescaled m_t

Cone Jet Algorithm
Fitrange ± 15 GeV

Calibration uncertainty, Updated w/ Pythia 6.416

- A bug in p_T-ordered parton shower was found after this study was published
  This invalidated the tunings.
- After retuning analysis redone
- Total spread reduced to ± 1.0 GeV



• – fitted m_t
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Cone Jet Algorithm
Fitrange ± 15 GeV

Calibration uncertainty, Updated w/ Pythia 6.416

- A bug in p_T-ordered parton shower was found after this study was published
  This invalidated the tunings.

- After retuning analysis redone

- Total spread reduced to ± 1.0 GeV

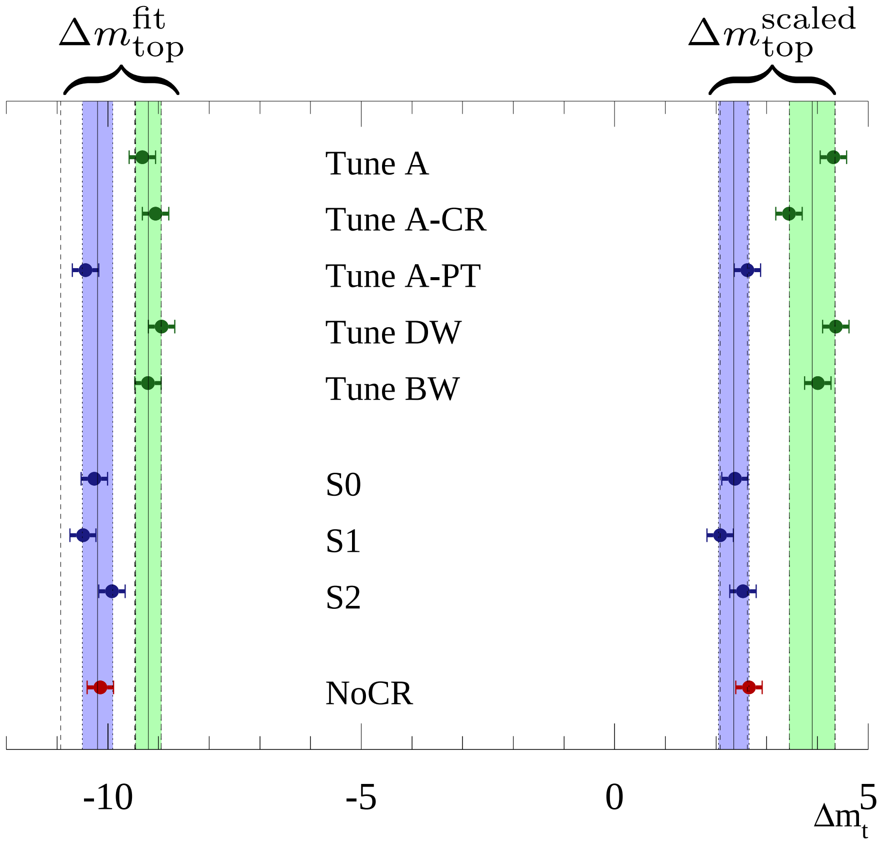
- Conclusions remain valid:

- 2 classes remain separated

  – Virtuality ordered (old) Parton Sh.
  – P_T ordered (new) Parton Shower

  Significant diff. of perturbative origin

- Within each group ~ 0.5 GeV of non-perturbative nature remain.



• – fitted m_t
sq – rescaled m_t

Cone Jet Algorithm
Fitrange ± 15 GeV

Summary

- Top mass measurements have reached total uncertainties < 1.5 GeV.
  At this precision non-perturbative effects may become important.
  - in the hard interaction.
  - in the underlying event.
  - in colour reconnection.

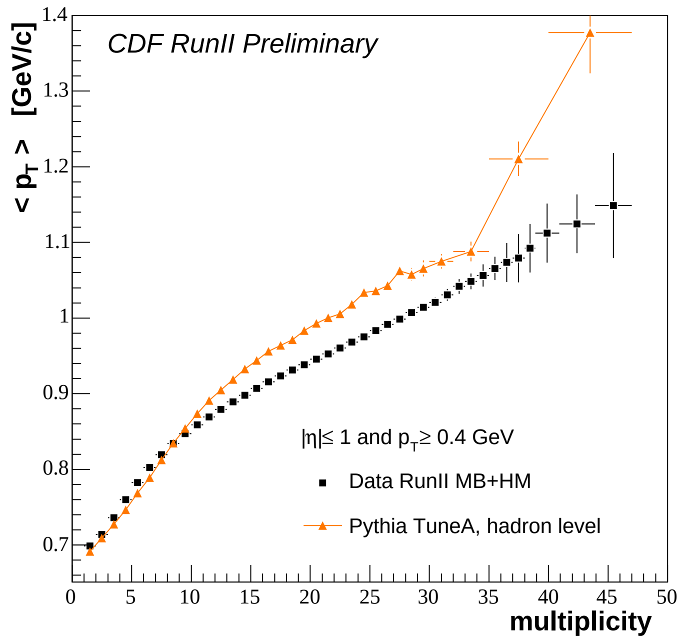
- UE models and new CR models in Pythia allow to check sensitivity.

- A toy top mass analysis was applied to various UE/CR models
  - Models show significant differences in the calibration offsets.
  - Thus yield systematic uncertainty of the toy top mass measurement.
  - The study exhibits a ~ 1 GeV model dependence (only 0.5 GeV non-pert.),
    only partly accounted for in current Tevatron top mass measurements

  - *Real life mass measurement may have different sensitivity to these effects*

Outlook

- CDF has recently published distributions used to tune the UE



- e.g. $\langle p_T \rangle (n_{\text{ch}})$

- Tune A doesn't fit 100%

- Recheck model difference after retuning models directly to data

- Tevatron Experiments start applying models to real life analyses

- Tunings will have to be retuned to LHC data before being applied to LHC